Integration Of Space Weather Into Space Situational Awareness

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ABSTRACT

Rapid assessment of space weather effects on satellites is a critical step in anomaly resolution and satellite threat assessment. That step, however, is often hindered by a number of factors including timely collection and delivery of space weather data and the inherent complexity of space weather information. As part of a larger, integrated space situational awareness program, Los Alamos National Laboratory has developed prototype operational space weather tools that run in real time and present operators with customized, user-specific information. The Dynamic Radiation Environment Assimilation Model (DREAM) focuses on the penetrating radiation environment from natural or nuclear-produced radiation belts. The penetrating radiation environment is highly dynamic and highly orbit-dependent. Operators often must rely only on line plots of 2 MeV electron flux from the NOAA geosynchronous GOES satellites which is then assumed to be representative of the environment at the satellite of interest. DREAM uses data assimilation to produce a global, real-time, energy dependent specification. User tools are built around a distributed service oriented architecture (SOA) which allows operators to select any satellite from the space catalog and examine the environment for that specific satellite and time of interest. Depending on the application operators may need to examine instantaneous dose rates and/or dose accumulated over various lengths of time. Further, different energy thresholds can be selected depending on the shielding on the satellite or instrument of interest. In order to rapidly assess the probability that space weather effects, the current conditions can be compared against the historical distribution of radiation levels for that orbit. In the simplest operation a user would select a satellite and time of interest and immediately see if the environmental conditions were typical, elevated, or extreme based on how often those conditions occur in that orbit. This allows users to rapidly rule in or out environmental causes of anomalies. The same user interface can also allow users to drill down for more detailed quantitative information. DREAM can be run either from a distributed web-based user interface or as a stand-alone application for secure operations. We will discuss the underlying structure of the DREAM model and demonstrate the user interface that we have developed. We will also discuss future development plans for DREAM and how the same paradigm can be applied to integrating other space environment information into operational SSA systems.

1. INTRODUCTION

The Dynamic Radiation Environment Assimilation Model (DREAM) was developed at Los Alamos National Laboratory to understand and to predict hazards from the natural space environment and artificial radiation belts produced by high altitude nuclear explosions (HANE) such as Starfish. DREAM was initially developed as a basic research activity to understand and predict the dynamics of the Earth's radiation belts. It uses Kalman filter techniques to assimilate data from space environment instruments with a physics-based model of the radiation belts. DREAM can assimilate data from a variety of types of instruments and data with various levels of resolution and fidelity by assigning appropriate uncertainties to the observations. Data from any spacecraft orbit can be assimilated but DREAM was originally designed to work with input from the LANL space environment instruments on Geosynchronous and GPS platforms. With those inputs, DREAM can be used to specify the energetic electron environment at any satellite in the outer electron belt whether space environment data are available in those orbits or not. Even with very limited data input and relatively simple physics models, DREAM specifies the space environment in the radiation belts to a high level of accuracy. DREAM is currently being tested and evaluated as we transition from research to operations.

The DREAM beta web service uses a single satellite for data input which is currently GOES (the Geostationary Operational Environmental Satellites). We are grateful to the NOAA Space Weather Prediction Center for making GOES energetic particle data available in real time for general use. LANL-GEO and GPS data are not used in these results. Several artifacts and limitations are primarily the result of this single-satellite input.

The data on these web pages are from the DREAM model run in a very particular and limited configuration that is intended to demonstrate a prototype real time capability. Compared to the full capabilities of DREAM the beta web

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14. ABSTRACT

Rapid assessment of space weather effects on satellites is a critical step in anomaly resolution and satellite threat assessment. That step, however, is often hindered by a number of factors including timely collection and delivery of space weather data and the inherent complexity of space weather information. As part of a larger, integrated space situational awareness program, Los Alamos National Laboratory has developed prototype operational space weather tools that run in real time and present operators with customized, user-specific information. The Dynamic Radiation Environment Assimilation Model (DREAM) focuses on the penetrating radiation environment from natural or nuclear-produced radiation belts. The penetrating radiation environment is highly dynamic and highly orbitdependent. Operators often must rely only on line plots of 2 MeV electron flux from the NOAA geosynchronous GOES satellites which is then assumed to be representative of the environment at the satellite of interest. DREAM uses data assimilation to produce a global, real-time, energy dependent specification. User tools are built around a distributed service oriented architecture (SOA) which allows operators to select any satellite from the space catalog and examine the environment for that specific satellite and time of interest. Depending on the application operators may need to examine instantaneous dose rates and/or dose accumulated over various lengths of time. Further different energy thresholds can be selected depending on the shielding on the satellite or instrument of interest. In order to rapidly assess the probability that space weather effects, the current conditions can be compared against the historical distribution of radiation levels for that orbit. In the simplest operation a user would select a satellite and time of interest and immediately see if the environmental conditions were typical, elevated, or extreme based on how often those conditions occur in that orbit. This allows users to rapidly rule in or out environmental causes of anomalies. The same user interface can also allow users to drill down for more detailed quantitative information. DREAM can be run either from a distributed web-based user interface or as a stand-alone application for secure operations. We will discuss the underlying structure of the DREAM model and demonstrate the user interface that we have developed. We will also discuss future development plans for DREAM and how the same paradigm can be applied to integrating other space environment information into operational SSA systems.

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service contains a variety of compromises and internal inconsistencies that will be described below. The primary objectives for putting this beta version on the web are (1) to develop the computational infrastructure for real-time operations and web-based services, (2) to provide some initial outputs that are available to the space weather community and (3) to solicit your comments and suggestions as we continue the development. This is very much a work in progress and the current outputs should not be used for research or operations.

2. DESCRIPTION of the PLOTS

The DREAM beta web service contains two basic plot types: flux and phase space density. Each plot type is selectable using the tabs above the plot.

In either mode, flux or phase space density (PSD) is plotted (using a color-coded scale) as a function of time and radial distance (R) or Drift Shell (L*), both in units of Earth Radii (1 Re = 6370 km). Plots cover approximately 1 month. The plots update automatically every time new data are assimilated. New GOES data is available approximately every 5 min. Status bars at the top of the plot show the status of data availability and progress of the assimilation. It is possible for new data to show up for an earlier time It is also possible for ancillary data such as Kp or calculations of the magnetic invariants to be updated for some time in the past. Progress of recalculating data values is shown in the Data Status bar. Whenever the primary or ancillary data change new assimilations from that time to the present must be calculated and that progress is indicated in the Assimilation Status bar.

When flux (j) is displayed it is in units of particles/(cm^2-s-sr-MeV)$^{-1}$. Six different energies ranging from 1 MeV to 6 MeV are selectable using the pull-down menu below the plot. Five different equatorial pitch angles values ranging from 55° to 75° are also selectable. Each selected energy and pitch angle range returns flux values for a different range of radial distances (R) for reasons described in the procedures and artifacts sections.

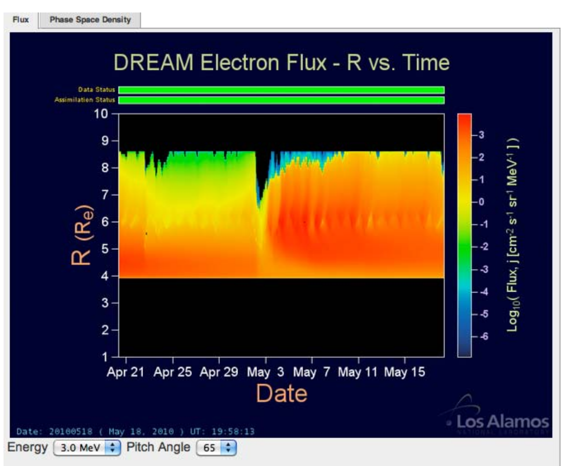

Figure 1: Final DREAM output is flux as a function of equatorial altitude (R) and time. Fluxes for 3 MeV and 65° equatorial pitch angle are shown here but are selectable with the pull down menus just below the plot.

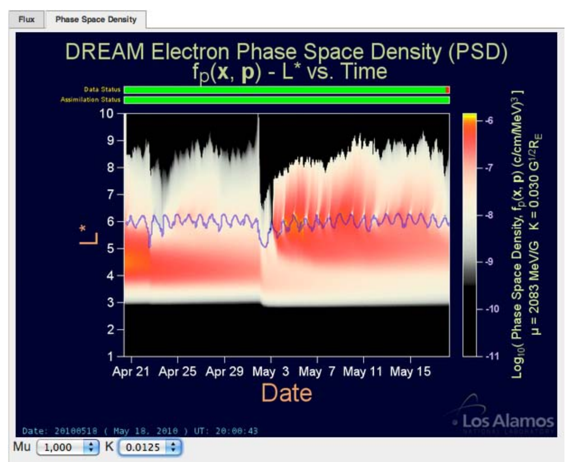

Figure 2: The actual assimilation in DREAM uses phase space density at fixed magnetic invariants (μ, K, L*). Assimilations are done for 25 different μ-K pairs and are visible in the Phase Space Density tab.

When phase space density is displayed it is in units of (c/cm-MeV)^3 for fixed values of the adiabatic invariants, μ, and K. Five different values of μ ranging from 1,000 to 20,000 MeV/G and five different values of K ranging from 0.0125 to 0.20 G$^{1/2}$ R_E are selectable using the pull-down menus. For PSD, DREAM returns valid (but not necessarily accurate) values for all L* from 1 to 10 in 0.1 R_E bins.

Selected space weather parameters such as Kp and Dst are shown in tabular or plot form below the DREAM results. Which parameters are shown may change as we continue to develop the DREAM web service. Similarly the links to the left or right of the plot and the content that those links point to may also vary. Screen shots as of May, 2010 are shown below.

3. PROCEDURES

The DREAM beta web service assimilates data from only a single GOES satellite. We use the NOAA-designated primary GOES satellite which, as of May 2010, is GOES-13. Future versions will assimilate available near-real-time data sources which might include multiple GOES satellites, LANL-GEO, GPS, the RBSP space weather broadcast, and others.

We fit a power law spectrum to the integral GOES energy channels which cover >0.8 MeV and >2 MeV. (Other GOES satellites have channels for >0.6 and >0.2 MeV.) We extrapolate the spectrum to arbitrarily high or low energies as needed. (More physically realistic procedures are certainly possible and errors due to extrapolation are a known limitation.)

The first adiabatic invariant, μ, is calculated from the fit spectrum and the model magnetic field. It is, of course, possible to use the measured GOES magnetic field but the beta version shown here does not. The second invariant, K, is also calculated using the model magnetic field. In calculating phase space density we assume (for the beta version) an isotropic pitch angle distribution.

We calculate the third invariant L* using the Tsyganenko 1989 model (T89) using the latest Kp values. One effect of using the T89 is a diurnal variation in the L* "position" of GOES. When GOES is on the day side it generally samples lower L* and when it is on the night side it samples higher L*. The specific values of L* also change with activity. At higher activity levels the "Dst effect" inflates the geomagnetic field with the result that lower L* values are sampled.

The plots of PSD show the L* value of GOES with a purple line.

Once we have calculated the magnetic invariants, (μ, K, L) we convert Flux (at fixed energy and pitch angle) to phase space density (PSD). It is actually the PSD values, not the flux values, that are assimilated in the DREAM model. This is because the physics model requires PSD and magnetic invariant coordinates.

The physics model in the DREAM beta web service is a simple radial diffusion model that uses the Brautigam & Albert [2000] formulation. It includes loss terms for the electron lifetime. Lifetimes are constants inside the plasmasphere and outside the last closed drift shell. Between the plasmapause and the magnetopause the lifetime is Kp dependent. (See Shprits et al., 2000.)

One assimilation is done for each μ-K pair. We currently calculate 25 separate assimilations for five values of μ and five values of K. The assimilations are computationally very fast and there is little trouble in scaling up to 100 or 1,000 assimilations for an operational version.

PSD is calculated for all bins from L* = 1-10. The model seldom produces appreciable PSD inside L*≈3. This is physically realistic and represents the point where inward radial diffusion is slow relative to the electron loss lifetime. We note that while the feature is realistic, the quantitative PSD values are not. We know this from other DREAM assimilation runs that use GPS data as well as geosynchronous data. The GPS observations at L*<5 significantly alter the assimilation results.

The magnetopause defines the limits of trapping for the radiation belts. The L* value of the last closed drift shell is also calculated using the T89 model. While the assimilation space extends to L* = 10, we set a very short electron lifetime outside the last closed drift shell. This creates a "ragged" outer boundary. We know from DREAM runs compared with near-equatorial POLAR observations between geosynchronous orbit and the magnetopause, that the PSD values in that region are generally quite good when realistic input spectra and pitch angle distributions are available.

The final step is to convert back from PSD to flux at fixed energy and pitch angle. At a given point in space different pitch angles have somewhat different L*. Similarly the conversion from μ to energy depends on the local magnetic field which is a function of both radius and local time. Therefore, converting back to flux is strictly possible only for a specified set of points in space. (E.g. along a spacecraft trajectory or a non-Keplerian set of points such as radial distance at fixed local time.) For computational simplicity the beta version here uses the (erroneous) assumption that L* = dipole L = R. Future versions will use the correct conversion procedure.

Conversion from K to equatorial pitch angle is linear. However, the range of pitch angle values in the final product is limited by the range of K values used in the assimilations. The conversion from μ to energy is proportional to the magnetic field strength and is L-dependent. Therefore, the range of L-shells for which flux can be calculated at a given energy and pitch angle is limited by the choice of the range of μ and K values used in the assimilations. As noted above there is no fundamental limit to the number and range of μ and K values that could be computed but, at some point, the extrapolation (in energy or pitch angle) from the omni-directional, integral-energy GOES measurements becomes physically unrealistic. The limitations on final DREAM output are illustrated in the figures below.

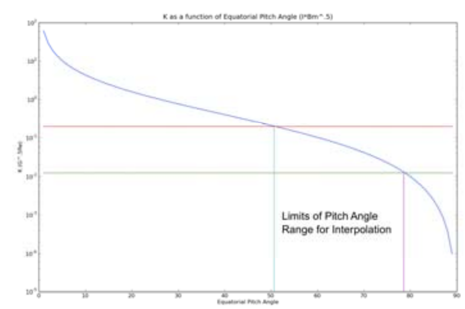

Figure 3: The relationship between the second invariant, K, and equatorial pitch angle α. Values are shown for L* = 6.6 but the relationship does not vary much as a function of L*. The current choice of limiting assimilations to K values between 0.0125 and 0.2 limits the range of equatorial pitch angles we can calculate to between about 50° and 80°. These limits are arbitrary and will be changed in future versions of DREAM

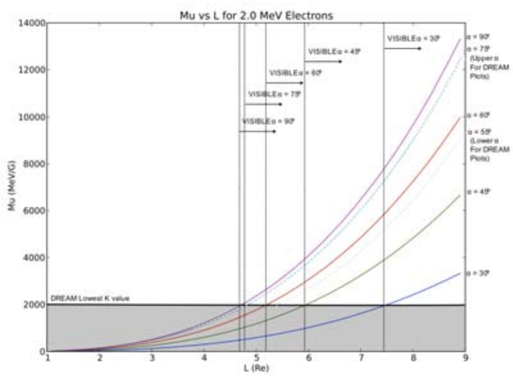

Figure 4: The first invariant is proportional to energy divided by magnetic field strength (E/B) and therefore varies strongly as a function of L*. This plot shows the relationship between μ (Mu) and L* for a fixed energy of 2 MeV and a family of curves for different equatorial pitch angles.

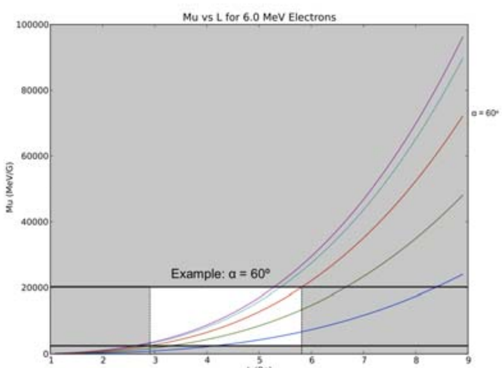

Figure 5: This figure illustrates how a choice of fixed energy and pitch angle imposes limits on the L range in which fluxes can be calculated. This plot shows μ as a function of L* for an energy of 6 MeV. The red curve shows values for a 60° equatorial pitch angle. The heavy black lines show the range of μ values used in the DREAM beta web service (2,000-20,000). The intersection of the red curve with those lines defines the range of L-shells which in this example lie between about 3 and 6 R_E.

4. BETA VERSION: ARTIFACTS AND LIMITATIONS

We have already noted some of the limitations of the DREAM electron flux output. They include:

Use of an assumed isotropic pitch angle distribution for the GOES data
Limits due to fitting a spectrum to only two GOES integral energy channels
A simplifying assumption of dipole L in converting from PSD to flux which is inconsistent with the T89 model L* used when converting the initial flux measurements to PSD.
Limits on the range of L-shells for which flux can be calculated. This is due to the limited range of μ and K values chosen for the assimilations

None of these limitations is a fundamental limitation of the DREAM model. The choice of the range of μ and K values can be changed as can the number of μ-K pairs (currently 25). Since a separate assimilation needs to be done for each μ-K pair there are computational limits but it should be possible to increase the range and number of μ and K values significantly while still fitting the computational limitations of a simple desktop computer.

Other limitations and artifacts come from the use of a single satellite as a source of data for the assimilation. Because of the asymmetry of the magnetic field, a geosynchronous satellite at fixed altitude still samples different drift shells (denoted by L*) on the day side and night side of the Earth. This diurnal variation of the L* sampled by GOES is most readily seen in the Phase Space Density plots but ruminants extend to the Flux plots also.

It is almost always true that the phase space density across the range of L-shells sampled by GOES in a single orbit is not constant but, rather, exhibits a radial gradient. When higher PSDs are measured their effects diffuse inward and outward in the model. When lower PSDs are measured their effects also propagate. This often creates “stripes” of higher or lower PSD that propagate to higher or lower L-shells. What it means physically is that radial diffusion cannot reproduce the PSD gradient that exists between the L*-shells measured at noon and midnight. In fact the existence of these artifacts provides important information on the sign and the magnitude of PSD gradients near geosynchronous orbit. We also note that the actual PSD gradients can be a function of μ and/or K and therefore the diurnal artifacts can appear differently for different values of μ and K.

We note that assimilating data from multiple geosynchronous satellites that sample different L-shells simultaneously reduces or eliminates these diurnal artifacts. Two (or more) geosynchronous satellites can measure the PSD gradient directly and include it properly in the model.

The artifacts of diurnal variations can still be seen in the flux data even at energies (i.e. 2 MeV) that were measured in the original input. There are two reasons for this. One is the current mismatch between the magnetic field model used to convert flux to PSD and the field model used to convert back from PSD to flux. The other is more subtle. At any point in space the flux at fixed energy and fixed pitch angle must be reconstructed from interpolated values of discrete μ and K values. Since the artifacts in the PSD calculations can be different for different μ-K pairs and the flux at any given time and location needs to interpolate between different μ and K values, the artifacts do not “cancel out”.

Future versions of the DREAM web services will use the same magnetic field model in all calculations. Some artifacts will remain if flux is calculated at an arbitrary position but if we calculate flux at the location of the input GOES data we should be able to reproduce the original measurements with high accuracy. A measure of this accuracy tests the numerics but also tests the effects of spectral fitting or the assumption of isotropic pitch angle distributions.

It is also possible to use a single GOES satellite as input and a different GOES satellite as a validation data set. Using the LANL-GEO observations we assimilate multiple geosynchronous satellites (reducing diurnal artifacts) and still have one or more geosynchronous satellites for validation. With proper validation data sets we can quantitatively test the errors introduced by different simplifying assumptions or by limited data availability.

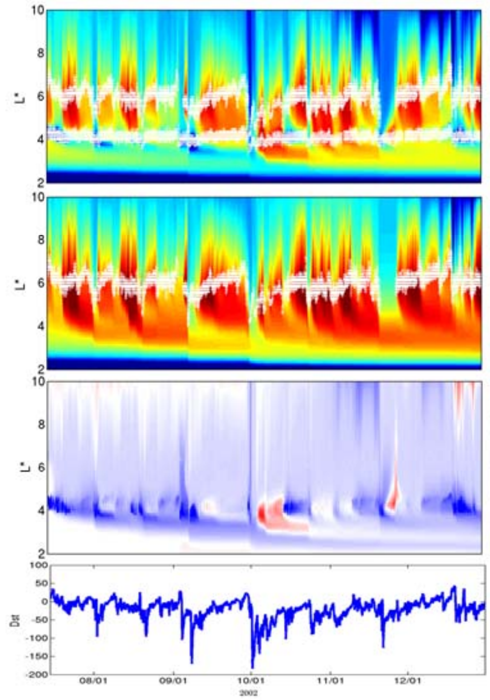

Figure 6: This figure shows PSD values from the DREAM assimilation using geosynchronous and GPS observations (top) and compares it with an assimilation using only geosynchronous observations (panel 2). The remaining panels show the ratio of PSD values obtained from the two model runs, and the Dst index. This figure is illustrative of the types of tests that can be conducted to determine where and when the models perform best. Similar tests can quantify the uncertainties (or errors) in the model as a function of energy, pitch angle, spatial location, and/or geomagnetic activity. Such studies will be conducted in the near future.

An example of one quantitative test using PSD values is shown in the figure above. In the top panel we have used three geosynchronous satellites and one GPS satellite in the assimilation. We show near-equatorial K values which GPS samples only close to 4 R_E. In the second panel we conduct the same assimilation with the same assumptions but without GPS observations. Next we show the ratio of the two assimilation results for this μ-K pair on a log scale. Geomagnetic activity (Dst) is plotted in the bottom panel. As we can see, using geosynchronous observations alone produces PSD values that can be too high by a factor of 100 or too low by a factor of 10.

We have done similar tests for larger K values (which also extends the L* range of available GPS observations) and found that using geosynchronous data alone generally produces the largest errors inside L≈5. We have also done similar comparisons of assimilations with and without POLAR observations outside geosynchronous orbit and find that the assimilations reproduce PSD values outside geosynchronous orbit surprisingly well.

It is important to note that true validation should be done on flux values rather than on PSD values. These initial comparisons are illustrative of what *could* be done and where the largest errors are expected. Some initial, quantitative validations of fluxes from DREAM has been published in the AMOS conference proceedings [Reeves et al., 2008].

The DREAM beta web service also has limitations on times that are available. The beta web service was developed specifically for real time data and real time specifications (nowcasts). This means that it is not currently simple to request a specific period of time or to store a database of values that spans many years. We are currently re-working the codes in order to make it possible to run a DREAM assimilation for a user-selectable period of time and a user-selectable set of available satellite data sets as either input or validation. We are currently working with the Air Force Space Weather Forecast Laboratory (SWFL) and NASA's Community Coordinated Modeling Center (CCMC) to perform more extensive validations once the greater flexibility is available.

5. FUTURE DIRECTIONS

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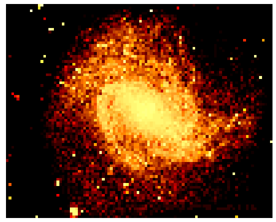

Fig. 1. Galaxy M83

6. REFERENCES

Number citations consecutively in square brackets [1]. Refer simply to the reference number, as in [3]. Do not use "Ref. [3]" or "reference 3" except at the beginning of a sentence: "Reference [3] was the first…". The title of the book or of the journal shall be italicized.

6.1 Sample References

1. Johnson, N.L. and McKnight, D.S., *Artificial Space Debris*, Orbit Book Company, Malabar, Florida, 1991.
2 Grun E. et al, Collisional Balance of the Meteoritic Complex, ICARUS, Vol. 62, 244-272, 1985.